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Huang, M. J., McCormack, S., Eames, P. C., & Norton, B. (2008). The Effect of Phase Change Material Crystalline Segregation on the Building Integrated Photovoltaic System Thermal Performance. In *Unknown Host Publication* (pp. 1338-1343). Elsevier.

[Link to publication record in Ulster University Research Portal](#)

Published in:
Unknown Host Publication

Publication Status:
Published (in print/issue): 21/07/2008

Document Version
Publisher's PDF, also known as Version of record

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The Effect of Phase Change Material Crystalline Segregation on the Building Integrated Photovoltaic System Thermal Performance

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Introduction

Elevated operating temperatures reduce the solar to electrical conversion efficiency of building integrated photovoltaic devices (BIPV). Active heat dissipation in BIPV using air or water cooling introduces the cost of pumping and increased system maintenance. In the most common passive approach to heat dissipation, a duct arranged behind the PV system or its mounting system allows natural convection and wind induced air-flow across the back of the PV panel. This method for cooling is inherently limited due to the poor heat transfer properties of air when only subject to natural convection which limits the rate of heat dissipation from the PV. Phase change materials (PCM) can absorb a large amount of energy at constant temperature during the phase change. PCM have received great interest for many applications such as energy storage and thermal protection of systems as well as for active and passive cooling of electronic devices (Zalba et al., 2003). An investigation of a PV/PCM system using phase change material (PCM) to passively limit the temperature rise of BIPV has been conducted (Huang et al., 2004, 2006 (a) (b) and (c)). It was found that using a PCM with a melting temperature of 26.6°C, with embedded metal fins, at an insolation of 750Wm⁻² and an ambient temperature of 19°C the PV achieved a temperature of 38°C while a standard flat PV panel temperature of 56°C was measured, significantly higher than the PV charactering temperature of 25°C. This study investigated the effect of crystalline segregation and convection in the PCM on the efficiency of heat transfer within the PV/PCM system.

Cho and Choi (2000) have investigated the thermal characteristics of paraffin in spherical capsules during both freezing and melting. It

was found that the average heat transfer coefficients for paraffin were larger by a maximum of 40% compared to those of water during the freezing and melting processes. The most important technical barrier when using PCMs for energy storage is their low thermal conductivities. The low thermal conductivity frequently makes it impossible to obtain the designed thermal output.

The properties of various PCMs, methods of heat transfer enhancement and design configurations of heat storage facilities to be used as a part of solar passive and active space heating systems have been summarised by Kenisarin and Mahkamov (2007). Commercial paraffins and paraffin waxes are more attractive for application in solar heating systems since these materials are produced in large quantities and are widely used elsewhere. Paraffin has the advantages of a wide range of melting temperatures, an almost negligible degree of subcooling and phase separation. Paraffins/waxes are saturated hydrocarbon mixtures, normally consisting of a mixture of numerous alkanes. They are sourced from crude oil, where they are contained within fractions arising from the production of lube oils. The information on the thermo-physical properties of some paraffins and paraffin waxes is presented by Kenisarin and Mahkamov (2007).

Experimental Methods

Three paraffin based PCMs were used in this analysis. Table 1 lists the thermophysical properties of Waksol A, RT25 and RT35 (RT25 this specific material is no longer available, but RT27, has similar properties). The selected PCMs are non-toxic, chemically inert with most materials and do not pose a danger to either health or the environment. Due to volume

expansion on melting only 85% of the test systems volume was filled with PCM.

A PV/PCM system was fabricated and used to study the effect of PCM porosity on the thermal performance of the PV/PCM systems ability to control temperature (Figure 1 and 2). The front and back walls of the PV/PCM test system were fabricated from 5 mm aluminium to provide a high rate of heat transfer to the PCM. This was enhanced by a series of changeable metal fins extending into the PCM from the front wall. The interior dimensions of the containers were 0.132m long by 0.04m wide by 0.3m high. The upper and lower horizontal and the vertical end faces of the PV/PCM system were made of 0.012m thick clear perspex to observe phase transition. Polystyrene foam 0.050m thick (thermal conductivity $0.027\text{Wm}^{-1}\text{K}^{-1}$) was used to provide insulation on the top, bottom and side areas of the system. The insulation on the vertical ends and top faces could be removed to enable observation of the system interior.

Table 1 Thermophysical properties of Waksol A, RT25 and RT35 (Anon, 2007)

		Waksol A	RT25 (Liquid)	RT35 (Liquid)
Property	Density			
	Solid kg m^{-3}	770	785	880
	Liquid kg m^{-3}	760	749	760
	Specific heat capacity			
	Solid $\text{J m}^{-3} \text{K}^{-1}$	1771000	1413000	1584000
	Liquid $\text{J m}^{-3} \text{K}^{-1}$	1848000	1797600	1824000
	Thermal conductivity			
	Solid $\text{W m}^{-1} \text{K}^{-1}$	0.33	0.19	0.2
	Liquid $\text{W m}^{-1} \text{K}^{-1}$	0.31	0.18	0.2
	Melting temperature $^{\circ}\text{C}$	32-36	26.6	35
	Latent heat of fusion J kg^{-1}	162000	232000	157000
	Kinematic Viscosity $\text{mm}^2 \text{s}^{-1}$ (at 70°C)	N/A	2.4	3.3
	Flash point $^{\circ}\text{C}$		164	178
	Volume expansion %		10	10

The ambient temperature and temperatures both within and on the external surfaces of the PV/PCM systems were measured using $0.2 \times 10^{-3} \text{ m}$ diameter wire T-type copper-constantan thermocouples calibrated to $\pm 0.1^{\circ}\text{C}$ using a standard resistance-temperature detector. The ten T-type thermocouples on the front and back surfaces of the PV/PCM system to measure the surface temperatures were equally distributed on the surfaces. Seven thermocouples were inserted in the space between the front and rear walls of the system with equal vertical spacing and denoted by A to G.

The experimental apparatus consisted of the PV/PCM experimental test system, a solar simulator, and a data acquisition system. An

independently powered programmable data-acquisition logging device was used to read and store data from the thermocouples and the pyranometer. The data from the data logging system was then transferred for analysis to a computer. The logger was set to read data every 60 seconds. The logger was located adjacent to the test system out of line of the simulated insolation.

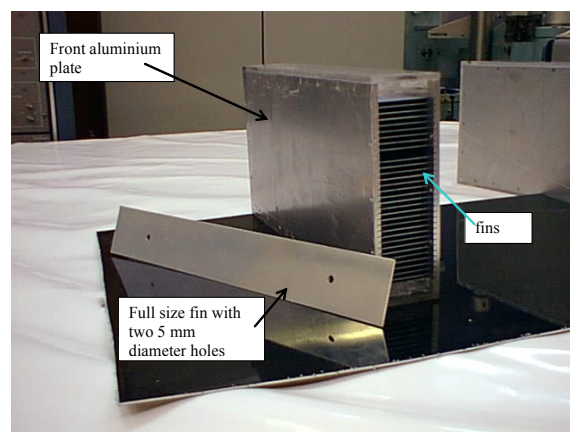


Figure 1 PV/PCM System with metal fins

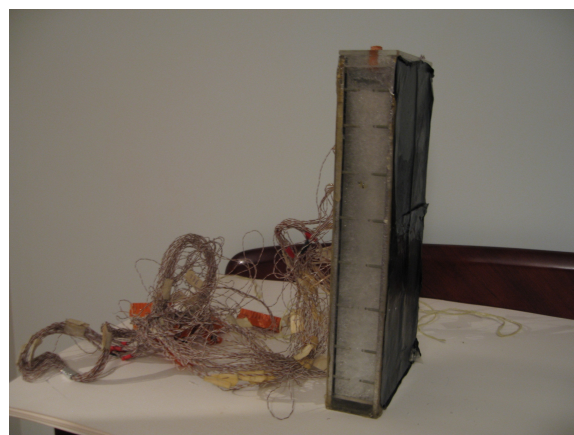


Figure 2 PV/PCM System with inserted thermocouples

Results

Paraffins/waxes are organic materials; due to minimal impurities melting occurs over a small temperature range. During solidification the relatively lower melting point PCM formed first with a dense structure on the area adjacent to the wall of the container, the effect of volume contraction increased the PCM porosity at the centre of the bulk PCM. Crystallisation formation that occurred on cooling to room temperature for bulk PCM RT25 is shown in Figure 3. It can be seen that the bulk PCM is of high porosity and that due to volume contraction

the centre part of the PCM upper surface is funnel shaped. The mechanical properties of PCMs have been shown to depend on many parameters such as temperature, the inner structure of the PCM and the deformation rate of the PCM (Kenisarin and Mahkamov, (2007)). The shape of the cavity in the top surface depends on the cooling rate (Figure 4). There is more porosity inside the bulk PCM with forced cooling than with natural cooling.

For different PCMs with similar cooling rates, the density of PCM RT35 formed close to the wall is higher than for Waksol A, and the cavity in the RT35 is larger than that in the Waksol A. When melting the PCM, the PCM becomes molten and the volume expands. If there is no effective path to release the expanded liquid, the pressure can cause system leakage. For the tested system, the PCM was only filled to 85% of the full system volume.



Figure 3 The porosity at the centre of the bulk PCM RT25.

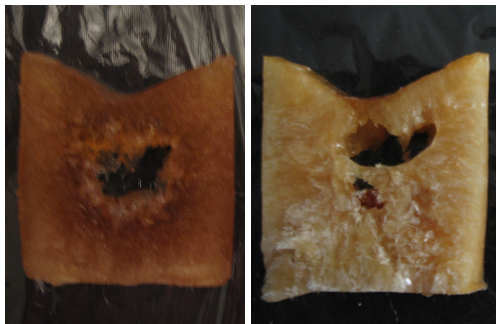


Figure 4 The porosity at the centre of the bulk for PCM Waksol A with 5 and -25°C solidification temperatures.

Testing of a PV/PCM with two fins in a horizontal position was undertaken. The fins were designed to increase the rate of heat transfer into the PCM by increasing the surface area over which heat transfer to the PCM occurs. The horizontal fins used to increase the heat transfer however also increase the heat

resistance due to the formation of bubbles under the fins during PCM melting (Figure 6). In the following experiments a PV/PCM system filled with 85% RT25 with full size vertical metal fins was used to study thermal performance. The system could accommodate a maximum of 32 fins with a 3.5mm spacing. The thickness of the steel fins was 0.5 mm. Systems without fins and with three different fin spacings (7, 10.5 and 21 mm) were tested. By increasing the number of fins the depth of cavity formed in the upper surface of the PCM can be moderated (Figure 7).



Figure 5 The porosity at the centre of the bulk for PCM Waksol A and RT35 with a -25°C solidification temperature.

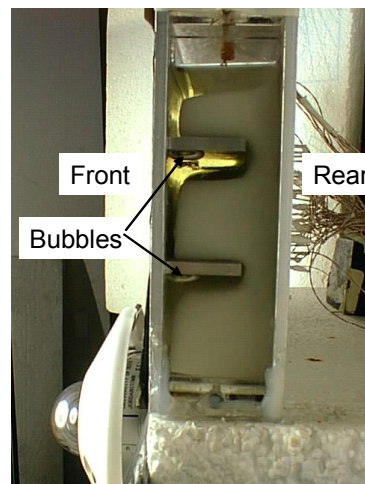


Figure 6 Bubbles under fins formed during melting

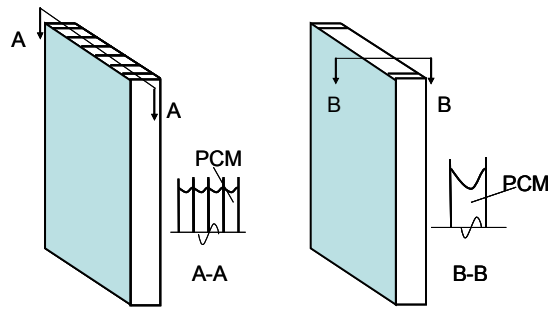


Figure 7 Schematic diagram of experimental systems with multiple vertical fins and no fins.
The temperature evolution for no fin module

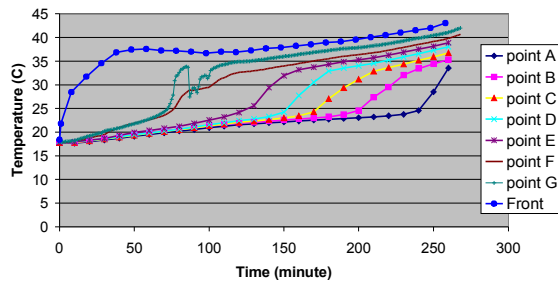


Figure 8 The temperature evolution for PV/PCM system with no fins

Figure 8 presents the temperature evolution in the centre of the PV/PCM system and on the front surface. It was found that using PCM RT25 with a melting temperature of 26.6°C at an insolation of 750Wm^{-2} and an ambient temperature of 19°C the PV/PCM system without fins can reduce the temperature rise of the PV to 38°C . Melting occurred from top to bottom with strong temperature stratification can be seen from figure 8 for the system with no fins. At the beginning of the experiment conduction dominated the heat transfer, and the temperature increase was linear with time. After 75 minutes, the effects of convection can be seen in Figure 8. After melting due to natural-convection in the melt, the temperature at point G has a sharp increase with a fluctuation from the phase change temperature. This is due to point G being positioned at the central top region close to the bottom of the funnel shaped cavity formed in the top surface during solidification. When the insolation is incident on the PV/PCM system the PCM adjacent to the front surface is molten with a nearly 10% expansion in volume compared to solid PCM. The liquid formed overflowed the bottom of the funnel shaped cavity and increased the temperature fluctuation (Figure 7). With continued energy input, the PCM at point F started to melt, due to convection the temperature increased towards the surrounding

molten PCM temperature. However the adjacent solid PCM is still below the temperature of phase change, the convective effect leads to increased transfer of heat to the upper PCM which leads to the temperature at point F increasing only slowly with time. With increasing fraction of molten PCM, the phase change temperature control effect is reduced. When the natural-convection effect becomes dominant, the period of time from phase change heat input to sensible heat input (around 33°C) is shorter for locations G to A.

The temperature evolution for module with 21 mm

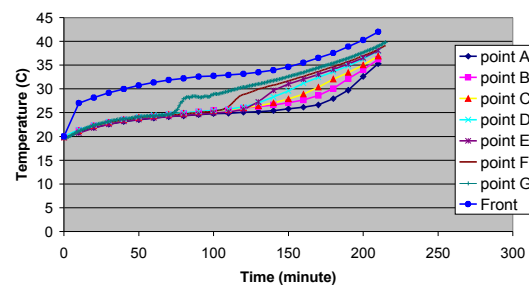


Figure 9 The temperature evolution for the PV/PCM system with 21 mm fin spacing

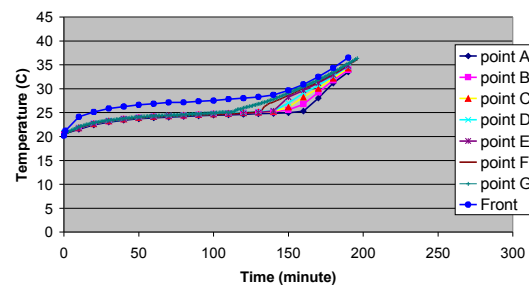


Figure 10 The temperature evolution for the PV/PCM system with 7 mm fin spacing

The effect of fin spacings of 7 and 21 mm on the temperature control of the front surface of the PV/PCM system have been studied. The temperature distribution along the system height with time for 750Wm^{-2} incident radiation is presented at the Figure 9 and 10. The fins effectively moderate the temperature rise. The temperature control effect is enhanced by reducing the interval between the fins, but the time for which control is maintained is shortened. When metal fins are added to the system the deep funnel shaped cavity in the upper PCM surface is changed to several small shallow funnel shapes between the fins (see Figure 5). The pressure that developed during the phase change was able to release avoiding leakage from the PCM container.

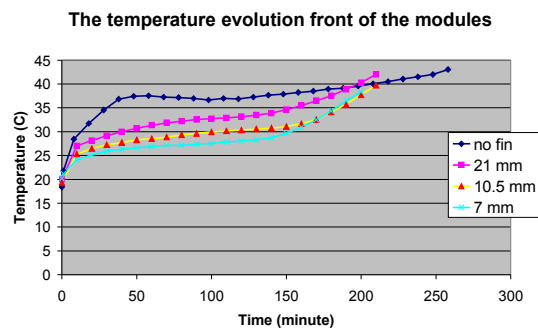


Figure 11 Temperature evolution comparison for systems with different fin spacings

The temperature evolution for the system with different fin spacings and no fins are shown in Figures 11. The increased number of fins can reduce the formation of a deep cavity in the upper PCM surface and stabilizes temperature fluctuations in the front centre region of the system. Fins can reduce the temperature rise on the front surface and reduce the thermal stratification inside the system. However the reduced period of time of temperature control and the increased weight of the metal fins needs to be studied.

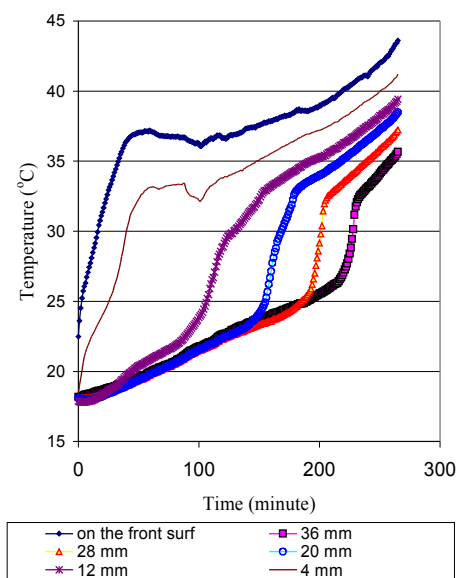


Figure 12 The temperature evolution at different distances from the front surface of the PV/PCM system with no fins

Figure 12 shows the temperature evolution at different distances from the front surface of the PV/PCM system with no fins. During the melting process the effect of the PCM temperature control can be seen on the front surface of the PV/PCM system. At the position of 4 mm from the heated surface, the PCM

melted rapidly and convection dominated the heat transfer to increase the temperature by over 14°C within 50 minutes. With increasing distance from the front surface, before the PCM melts, conduction dominates the heat transfer. With increasing volume of molten PCM the effect of convection increases. The time for temperature increasing from the phase change latent input to sensible input for the liquid PCM is reduced. The thermal stratification is clearly evident due to the natural convection in the molten PCM in the PV/PCM system.

Conclusions

In this study the performance of PCMs in a test system during melting and solidification are presented. The effect of thermal resistance on PV/PCM temperature control is found with the effects of crystallisation and the melting process studied. Fin arrangements to prevent increased thermal resistance due to bubbles formed during the melting process are evaluated. The thermal performance of the PCM in the finned PV/PCM system was monitored during the melting process and a detailed experimental evaluation of the process within the PV/PCM system undertaken. It was found that natural convection started during the early stages of the melting process and increases in magnitude with the melting process.

A better fundamental understanding of the processes within a PV/PCM system can be used to improve the optimum PV/PCM system design.

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